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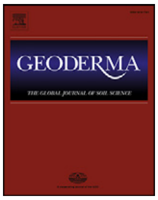

Chemical weathering in the volcanic soils of Isla Santa Cruz (Galápagos Islands, Ecuador)

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ABSTRACT

Forty-three soils (130 horizons), sampled by the geo-pedological mission organized by the State University of Gent (Belgium) in 1962 on Isla Santa Cruz (Galápagos Islands), were analysed in order to determine their degree of chemical evolution. Several weathering indices (Weathering Index of Parker – WIP –, Chemical Index of Alteration – CIA –, Chemical Index of Weathering – CIW –, Plagioclase Index of Alteration – PIA – and Silica–Titania Index – STI –) and multivariate statistical analysis (principal components analysis), based on chemical composition, were used. With the only exception of the STI, the indices were highly correlated ($r > 0.85$). The highest WIP and STI values (20.9 ± 8.2 and 70.2 ± 2.2 respectively) were found for soils developed on basalt flows near the coast. Slightly lower values (WIP 16.8 + 5.1 and STI 61 ± 3.4) were shown by brown soils developed from basaltic flows at elevations between 140 and 225 m a.s.l. While the lowest values (WIP 9 ± 5 and STI 47 ± 6.8), representing the more weathered materials, were found for soils located at the highest elevations (>400 m a.s.l.) and mostly developed on pyroclastic materials (tuff and tephra).

As the chemical composition of the geological material (basalt and tephra) is highly homogeneous, the degree of weathering is likely to depend on climatic conditions controlled by altitude and orientation. On the windward slopes of the island a gradient of increasing weathering is observed from the arid conditions predominant at the coast to elevations of 400–500 m a.s.l., where much more humid conditions prevail. Principal component analysis on elemental composition also supported the interpretation that the degree of weathering (first component) and soil horizonation (second component) are both related to climatic conditions. Both, the variation of the chemical indices and the principal components of the geochemical composition are related to the bioclimatic zones: soils with the lowest degree of weathering are located in the arid coastal zone; slightly higher intensity was found for soils located in the transition and *Scalesia* zones; while the most weathered soils appear in the brown zone. Compared to other volcanic soils studied in the literature, soils from Isla Santa Cruz are in the upper range of chemical weathering intensity, only comparable to soils from Azores Islands and Canary Islands (Tenerife and La Gomera) developed on basalts, under oceanic conditions.

1. Introduction

By virtue of the importance of the Galápagos Islands to world science following the work of Charles Darwin, it is unsurprising that their fauna, flora and geology have been well studied. Soils, however, had been ignored (Sabau, 2008) until a geo-pedological mission was organized in 1962 by the State University of Gent (Belgium), that made a systematic soil survey of the, at that time, accessible part of Isla Santa Cruz. An evaluation of the existing knowledge on Galápagos soils and an interpretation from a micromorphological point of view were recently published by Stoops (2013, 2014), while Eswaran et al. (1973) studied the mineralogy and Adelinet et al. (2008) the hydrodynamic properties of a few soils. However, information on the chemical composition (Rodríguez Flores et al., 2006) and on the weathering processes in particular is very scarce. Weathering of soils results from a complex set of interactions between the lithosphere, atmosphere, hydrosphere and biosphere (Quantin, 1974; Birkeland, 1992; Chesworth, 1992; Macías and Chesworth, 1992; Shoji et al., 1993).

Weathering processes modify the mineralogy, petrography (microfabric) and geochemistry of rock materials (Birkeland, 1974; Chesworth et al., 1981; Nahon, 1991; Chesworth, 1992). Recognition, identification and evaluation of weathering-induced changes are essential for evaluating soil fertility and development, demonstrating the impact of climate on bedrock weathering, and/or simply providing a better understanding of elemental mobility during weathering (Price and Velbel, 2003). Chemical weathering indices are the most commonly used for characterising weathering profiles by incorporating bulk major element chemistry into a single metric for each sample (Parker, 1970; Kronberg and Nesbitt, 1981; Nesbitt and Young, 1984; Harnois,

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1988; Fedo et al., 1995; Jayawardena and Izawa, 1994; Ohta and Arai, 2007).

The objective of this work was to study the chemical weathering of volcanic soils in Isla Santa Cruz, using the soils collected by the Belgian scientists (J. Laruelle, P. De Paepe and G. Stoops) mission. The aim is to help increase the knowledge on the formation and evolution of the soils on the Galápagos Islands.

2. Materials and methods

2.1. The physical environment: geology and climate

Galápagos is an archipelago of oceanic islands formed by the interaction between the Galápagos hotspot and the Cocos-Nazca ridge. Isla Santa Cruz belongs to middle aged islands and consists of a core of marine sediments, the Platform Series, covered by basaltic lava flows, known as the Shield Series. In the more elevated parts of the island, many ash cones are present. The age of the Shield Series ranges between 590 ± 27 ka and 24 ± 11 ka (White et al., 1993; Geist et al., 2011). These volcanic islands have not been active in historical time (White et al., 1993; Adelinet et al., 2008; Sallarés et al., 2009). The petrology and geochemistry of the rocks have been studied by White et al. (1993) and De Paepe (1968a, 1968b), who concluded that the volcanic materials are alkaline and tholeiitic basalts. White et al. (1993) analysed the chemical composition of major elements in twenty samples of the Shield Series of the island. De Paepe (1968a, 1968b) also studied the petrography of the lava of Isla Santa Cruz. In general, the lava has a porphyric fabric with phenocrysts of plagioclase (albite) and olivine (Mg-rich, colourless to faint green, and seldom zonated). In many cases olivine crystals show quasi-coatings of iddingsite as the result of deuteric alteration (Chesworth et al., 2004). Clinopyroxenes (Ti-augite) may compose 25% of the rock. Opaque minerals are restricted to the groundmass, mostly isometric magnetite and titanomagnetite, and skeletal ilmenite (De Paepe, 1968a, 1968b).

Stoops (2013) described the coarse material (>5 μm) of Isla Santa Cruz soils and found fragments of holocrystalline or mesocrystalline basalt. The holocrystalline alkali basalt corresponds to the massive, deeper part of the lava streams, whereas the often vesicular mesocrystalline types correspond to the surface of the lava streams and cinders. Holocrystalline basalt is the main type of rock fragments found in the coastal area and the lower slopes, whereas mesocrystalline basalt occurs on the middle and upper slopes, often mixed with holocrystalline basalt. This could indicate that in the lower zones basalt streams predominate, and that their pahoehoe surface is totally removed by weathering and erosion.

The increasing mineral weathering sequence in the basalt observed by Stoops (2013) is: feldspar–augite–olivine. The fact that the sequence does not follow the series of Goldich may be caused by the relative large size, the absence of cleavages (Welch and Banfield, 2002) and iddingsite coatings of the olivine crystals. If well protected by iddingsite that could explain why olivine breaks down less readily that conventionally more stable minerals. Iddingsite seems to remain stable.

The climate of Galápagos Islands is unusually dry and cold for their equatorial position. This is due to the prevailing south-east trade winds and cold oceanic currents that converge in the archipelago (Adelinet et al., 2008). There are two main seasons on the islands with major differences in temperature and rainfall. From January to June the climate is warm with occasional heavy rain showers. From June to December the air is cooler and an inversion layer is formed. It brings a moisture-laden mist to the highlands whereas the lowland areas remain dry. Average annual rainfall ranges from 500 mm on the coast to 1500–2000 mm in the highlands (above 500 m a.s.l.) on the southern windward side. The northern leeward side of the island only receives rainfall during heavy storms in the hot season (Pryet et al., 2012). Rainfall can quadruple during El Nino years (Trueman and d'Ozouville, 2010; Pryet et al., 2012).

Isla Santa Cruz is characterised by a broad low elevation coastal apron surrounding a main central shield, which culminates at Cerro Crocker 855 m a.s.l. Two long-term weather stations are operated since 1965. The first is located in Puerto Ayora (5 m a.s.l.) and the second in Bellavista (180 m a.s.l.). Recorded median annual rainfall totals are 277 mm and 800 mm, respectively. The coastal station (Puerto Ayora) receives the major part of annual precipitation during the convective rains of the hot winter season. This is the opposite at the second station, where most of the rainfall is recorded during the cool rainy season (Trueman and d'Ozouville, 2010). Due to the orographic effect, contrasts are more acute during the rainy season, when a fog layer is observed along the windward slope from 300 to 400 m a.s.l. up to the summit (Trueman and d'Ozouville, 2010; Pryet et al., 2012). The summit area remains clear of clouds occasionally, but the upper limit of the fog layer (the inversion layer) is most often above the top of the island (Pryet et al., 2012). Adelinet et al. (2008) showed that the physical properties of the soils of Isla Santa Cruz were in good agreement with the variation in rainfall according to the elevation, which appears as the main factor controlling the soil development.

2.2. Soil sampling

Forty-three soils sampled by the Belgian geo-pedological mission of 1962 from the coast and along the windward slopes of Isla Santa Cruz (Galápagos Islands) (Fig. 1, Table SI1) were used for the study:

- Six in the coastal area near Puerto Ayora (PAy) (GP67, 59, 68, 17, 65 and 61), an arid zone with xerophytic vegetation. Soils GP67, 59 and 68 are shallow (<15 cm) red "*lithosols*" and GP17, 65 and 61 deeper (<80 cm), interstitial (between basalt lava) clayey red soils (Table SI1).
- Nine in the surroundings of Bella Vista (BV) (GP4, 6, 1, 2, 8, 16, 55, 18 and 54); they are brown soils developed from basaltic lava with AC profiles and situated between 140–240 m a.s.l. (Table SI1). In the upper part of the profile the influence of pyroclastic materials increases with altitude (Stoops, 2013, 2014).
- Six along a catena to Crocker Mountain (CrM) to the north of BV (GP56, 57, 50, 49, 48 and 47); they are soils develop on basaltic lava and tephra deposits. Most of them are "*brown forest soils*" with A(B)C type profile (Table SI1).
- Six along a catena to the Camote volcano (CMt) NE of BV (GP14, 13, 12, 11, 10 and 9); they are "brown forest soils" and "regosols" developed from pyroclastic material (basaltic tephras) (Table SI1).
- Four soils in the vicinity of El Occidente (OC) (GP29, 31, 34 and 32); they are mostly developed from basaltic lava with A(B)C profiles (Table SI1).
- Seven along a catena to Santa Rosa (SR), NW of Bella Vista (GP37, 39, 40, 46, 45, 41 and 44); these soils have AC profiles, include "regosols" and "brown soils" and are developed from pyroclastic materials or a mixture of pyroclastic materials and fragmented basalt (Table SI1).
- Five in the Table and Rambeck Mountain (TRM) in the NE of the island (GP19, 21, 22 and 24). TRM soils include a group of profiles, developed on basalt and located at 370 m a.s.l. in a flat depression with gilgai-like microtopography (Table SI1).

Most PAy, BV and OC soils are developed on basalts; CrM soils develop on basaltic tephras and slope deposits; and CMt soils on basaltic tephras. The sampling was also representative of the pedoclimatic zones of Laruelle (1964, 1967) and four of the bioclimatic belts of the area: the arid coastal zone, the transition zone (situated between the arid coastal area and the more humid higher areas) (TZ, 100–240 m a.s.l.); the *Scalesia* zone (SZ, 240–400 m a.s.l.); and the brown zone (BZ, 400–500 m a.s.l.) (Table SI1).

Soil samples were stored in darkness in a cool, dry place at Ghent University under the supervision of Professor Georges Stoops. More